Swarm Robotics for Planetary Surface Exploration and Mapping

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Abstract

The use of swarm robotics enables high-resolution for terrain mapping for improved planetary site selection and surface exploration. This work presents a multi-robot framework that uses LiDAR and voxelized DEM data to identify and rank potential landing zones based on several terrain factors and also overall efficiency. The environment is separated into sectors, assigning one robot per region for efficient exploration. BFS with sensor simulation estimates coverage which was able to achieve ~99% surface coverage with <3% overlap, demonstrating the potential use case of swarm mapping for future exploration and mapping.

Introduction

Swarm robotics offers a promising solution to the challenge of in-site data gathering for planetary exploration. Unlike orbital imagery and altimetry data, coordinated robots can produce higher-resolution and real-time terrain map generation. This localized approach is crucial for pre-landing reconnaissance and environmental surveying, offering deeper insight into unfamiliar surface conditions. By merging sensor data with a terrain-selection algorithm, swarm systems could reduce mission risk—specifically for high-value payloads.

Methodology

A Digital Elevation Model (DEM) is converted into a voxel-zed 3D terrain with smoothing applied. The potential landing zones are identified based on how leveled the site and its surrounding area are. Each of them gets evaluated to determine the best potential coverage, while maintaining efficiency. The terrain is then divided into angular sectors, assigning one robot per sector for balanced exploration.

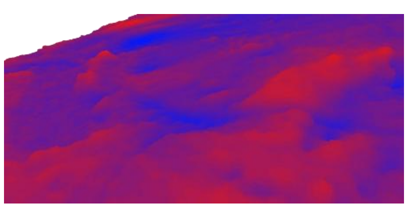

Figure 1: Close-up of voxelized Mars Surface

Each robot explores its assigned sector and a flood-fill algorithm approach to identify all reachable terrain. From each position, LiDAR scanning is to estimate surface coverage. A spatial indexing method limits computations to nearby cells, improving efficiency.

$$S = \frac{w_D \cdot D + w_C \cdot C + w_P \cdot P - w_O \cdot O}{w_D + w_C + w_P + w_O}$$

S	Landing Score
D	Sector Distribution
C	Potential Coverage
P	Path Efficiency
O	Overlapping Scans
w_D	Weight for Sector Distribution
w_C	Weight for Potential Coverage
w_P	Weight for Path Efficiency
w_O	Weight for Scan Overlap

Experiment & Results

Experiments were conducted on a Mars DEM that got voxelized into ~574K surface cells and over 80 landing candidates were found. Zones that at lower elevation (Blue) tends to have a higher likelihood over higher areas (Red) for selecting potential landing areas.

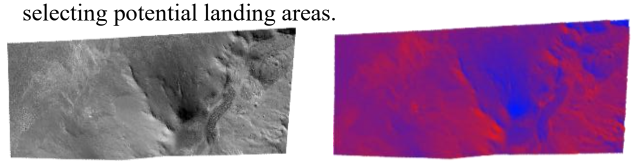

Figure 2 (Left to Right): Mars surface image; Voxelized conversion

Once a site gets selected, three robots achieved up to 95% surface coverage with less than 3% overlap. Sector-based partitioning produced balanced workloads (~38%, 31%, 31%) and minimized redundant scanning. Natural terrain

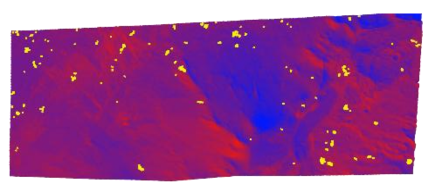

Figure 3: Possible landing spots denoted by yellow

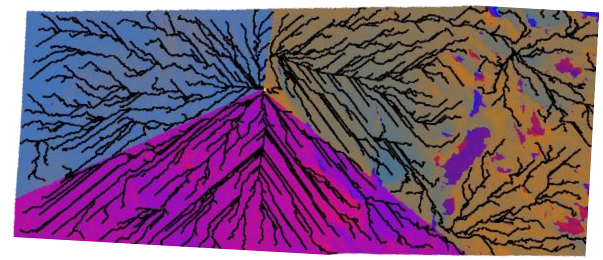

Figure 4: Scanned and path of Mars

features such as steep mountain tops and craters are ignored, thus showing gaps within the coverage scan. Approximately 99.5% of terrain was traversable under a 12.5° slope threshold. Results demonstrate that sector-based coordination enables efficient, scalable multi-robot mapping with minimal redundancy.

Conclusion & Future Work

This work presents a multi-robot coverage system for autonomous planetary surface exploration. The system was validated on a Mars DEM with 3 simulated robots, demonstrating terrain-aware sector partitioning, branching path generation, and coverage estimation.

Future work would consist of replacing the flood-fill algorithm with frontier-based exploration to replicate a potential path of rovers. Furthermore, incorporate a 3D simulated environment to validate the use-case and to be able to achieve real-time map generation of a celestial body.

References

[1] USGS Astrogeology Science Center, "Mars 2020 Terrain Relative Navigation HiRISE Orthorectified Image Mosaic," Jul. 24, 2020.

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